RESEARCH

Yield, Root Growth, and Soil Water Content in Drought-Stressed Pasture Mixtures Containing Chicory

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ABSTRACT

Chicory (*Cichorium intybus* L.), a deep-rooted forb, has potential for inclusion in pasture mixtures because of its reported drought tolerance and high productivity during summer months. This study examined how adding chicory to pasture mixtures affected forage yield, root growth, and soil moisture extraction under drought. The experiment was planted in August 2002. Movable rainout shelters were used to control water application in the field. Adding chicory to orchardgrass (*Dactylis glomerata* L.)–white clover (*Trifolium repens* L.) or perennial ryegrass (*Lolium perenne* L.)–white clover mixtures increased drought tolerance in 2003 when chicory constituted 24 to 39% of harvested forage biomass. Chicory mortality was high, decreasing from 39% of harvested forage yield under drought stress in early summer 2003 to 9% in late summer 2004. Improved yield under drought stress was not observed in 2004 when chicory constituted only 9 to 16% of the mixture. The three-species mixtures in 2003 had greater root counts than the two-species mixtures at soil depths below about 70 cm under well-watered conditions, but a greater proliferation of roots at depths below 70 cm was observed for the two-species mixture under drought stress. Both mixtures appeared capable of nighttime transfer of soil water from deep to shallow soil layers, thereby improving water availability to shallow roots. However, improved drought tolerance of the three-species mixture was probably related to improved water use efficiency rather than to greater access to and extraction of deep soil moisture.

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Increasing plant species diversity has been proposed as a means of increasing the productivity and stability of grazing lands facing drought stress (Ruz-Jerez et al., 1991; Daly et al., 1996; Caldeira et al., 2001). Sanderson et al. (2005) reported that two-species grass–legume mixtures produced less herbage than three-, six-, and nine-species mixtures during a dry year, but they found no difference in yield among mixtures when rainfall was plentiful. Inclusion of chicory (*Cichorium intybus* L.) in the more species rich mixtures appeared to be important for realizing improved yield under drought. In an experiment where movable rainout shelters were used to control moisture applications in the field, Skinner et al. (2004) found that a five-species mixture dominated by chicory had greater productivity than simple grass–legume mixtures. The increased productivity was observed at all moisture levels but was greatest under drought stress. The mixture containing chicory also had a greater proportion of its root biomass located below a depth of 30 cm than did other mixtures in the study. Skinner et al. (2004) concluded that including the additional functional attribute of a deep-rooted, drought-resistant species such as chicory was more important than species richness per se for improving forage yield and stability.

Chicory has increasingly been investigated for inclusion in pasture mixtures because of its reported drought tolerance and high productivity during summer months (Jung et al., 1996; Belesky et

Published in Crop Sci. 48:380–388 (2008).
doi: 10.2135/cropsci2007.04.0201

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al., 1999; Li and Kemp, 2005). Belesky et al. (1999) found that chicory was compatible with cool-season grasses and legumes and could be successfully grown in cool season–based forage systems. Including chicory in mixed swards improved seasonal yield distribution, especially in midsummer when drought stress reduced productivity of the dominant cool-season forages.

A potential drawback to the increased use of chicory is its reported poor persistence. Herbage production of 7 to 9 t ha^{-1} is common for the first 2 to 3 yr under grazing, but it decreases significantly as plants age (Li and Kemp, 2005). Under high fertility, chicory planted as part of a mixed sward declined from nearly a pure stand in the first production year to less than 5% of harvested biomass by the third year (Belesky et al., 2000). Chicory also failed to persist beyond the second production year in grazed pastures in eastern Pennsylvania containing either 3 or 11 species (Skinner et al., 2006). Li et al. (1997) concluded that a decrease in chicory density under grazing management appeared to be inevitable. Conversely, Skinner et al. (2004) found that the proportion of chicory increased from 31% of harvested biomass in May of the first year following fall sowing to 49% in May of the third year. In that experiment, no fertilizer N was applied and all N was provided by the legume component of the mixture. Belesky et al. (2000) also found that chicory survival improved as fertilizer N applications decreased.

The presence of a deep-rooted species in pasture mixtures can confer multiple advantages on the entire system. Berendse (1982) suggested that combining deep- and shallow-rooted species in a mixture could increase nutrient extraction from deep soil layers by the deep-rooted species, even beyond what would normally be observed when the same species was grown in monoculture. In addition, through the process of hydraulic lift, deep-rooted species can redistribute water from relatively moist, deep soil layers to dry layers near the surface (Richards and Caldwell, 1987; Caldwell et al., 1998). That moisture then becomes available for uptake by more shallow rooted species. Alternatively, preferential moisture extraction from deep soil layers by the deep-rooted species could leave more water available near the soil surface for uptake by the shallow-rooted species.

The purpose of this research was to determine the influence of chicory as a component of pasture mixtures on yield, root distribution, and moisture uptake under drought conditions. It was hypothesized that the inclusion of chicory would increase yield under drought but not under well-watered conditions and that the deep root system of chicory would increase access to and uptake of water from deep in the soil profile.

MATERIALS AND METHODS

Experiments were conducted under movable rainout shelters and in adjacent nonsheltered plots at the Russell E. Larson Experimental Farm at Rock Springs, PA. The soil was a Murrill silt loam (fine-loamy, mixed, semiactive, mesic Typic Hapludults). The soil was generally about 3 m deep with sandstone and shale rock fragments throughout and occasional limestone rock pinnacles that limited soil depth to less than 1 m in some places. Volumetric soil water content at a soil water potential of −0.033 MPa was 0.31 m^3 m^{-3} in the top 25 cm of the soil profile, rising to 0.34 m^3 m^{-3} as clay content increased below 25 cm. Volumetric soil water content at −1.5 MPa was 0.12 m^3 m^{-3} at the 25-cm depth. Soil tests before planting in 2002 indicated that P and K levels were at or below optimum levels. Therefore, on 1 Aug. 2002, 45 kg ha^{-1} P and 180 kg ha^{-1} K were applied to all plots. In May 2004, an additional 20 kg ha^{-1} P and 100 kg ha^{-1} K were applied. No nitrogen fertilizer was applied.

Two 10.2- × 26.8-m rainout shelters are located at the site. These movable shelters were covered with heavy-duty plastic each spring and were automatically triggered by rainfall during experimental treatments to cover the plots and exclude natural precipitation. Rain gauges were placed within and outside the shelters to monitor precipitation. The shelters automatically opened following rainstorms, exposing experimental plots to ambient radiation and temperature conditions whenever it was not raining. The nonsheltered control plots were located immediately adjacent to the rainout shelters.

Experimental plots (3 × 3 m) were broadcast seeded on 20 Aug. 2002. Plots were hand sown at a rate of 1000 seeds m^{-2}. Plots were sown to two-species grass–legume mixtures containing either orchardgrass (*Dactylis glomerata* L.)–white clover (*Trifolium repens* L.) or perennial ryegrass (*Lolium perenne* L.)–white clover, or to three-species grass–legume–chicory mixtures. The two-species mixtures contained 500 seeds m^{-2} per species, whereas the three-species mixtures included 300 seeds m^{-2} for the white clover and one grass and 400 seeds m^{-2} for the chicory. Plots were irrigated as needed during late summer and early fall to ensure seedling establishment. Plots were mowed to a 5-cm stubble height on 22 October to help suppress annual weeds. All treatments were replicated four times. On 11 Sep. 2002, one minirhizotron root observation tube was installed in each plot at a 30° angle from perpendicular to a depth of about 105 cm. At the same time, one neutron probe access tube was installed in each plot to monitor soil moisture content at 25-, 50-, and 75-cm depths.

On 30 Apr. 2003, one screen cage soil psychrometer (Wescor Scientific Products, Logan, UT) was placed at a depth of 25 cm in each plot under the rainout shelters by digging a trench along one side of the plots and then inserting the psychrometer several centimeters into the wall of the trench. The trench was then backfilled and the sod replaced. Soil water potential was recorded at 30-min intervals whenever the rainout shelters were operational. Psychrometers were individually calibrated before installation against solutions of known osmotic potential. Output was adjusted to a common temperature of 25°C to remove the effect of temperature on apparent soil water potential. Soil psychrometers were removed from the plots in fall 2003, cleaned, stored inside over winter, and then reinstalled in April 2004.

In 2003, all plots were mowed to a 5-cm stubble height on 30 April to remove standing dead material and early-season growth. Rainout shelters were activated on 3 June to initiate the drought treatment, and plots were mowed on 4 June. On 7 June, plots received 3 mm precipitation due to shelter malfunction;

otherwise, rain was excluded from the drought-stressed plots until 2 July. On 2 July, plots were harvested by clipping one randomly selected 0.1-m^2 quadrat within each plot to a 5-cm stubble height. The remainder of the plot was then mowed to the same stubble height. Clipped samples were separated by species, then dried and weighed. Following the harvest, drought-stressed plots received 56 mm of irrigation water to bring soil moisture back to field capacity. All plots were kept well watered throughout July. The drought treatment was repeated beginning 30 July when plots were mowed and the rainout shelters reactivated. Heavy rainfall (91 mm) during the first week of August caused water to flow under the sides of the rainout shelters, wetting plots located near the shelter edge. To reestablish uniform soil moisture conditions, all plots were irrigated on 8 August, and 13 mm rain was allowed to fall on the plots on 9 and 10 August, bringing soil moisture to field capacity in all plots. Drought treatments resumed on 11 August and continued until plots were harvested on 9 September. In 2004, plots were mowed on 5 May and 28 May to remove early-season growth. Experimental procedures were similar to 2003, with drought treatments running from 1 June to 2 July and from 29 July to 3 Sep. 2004. For simplicity of presentation, the first drought treatment of each year will be referred to as the early-summer treatment and the second as the late-summer treatment.

Control plots were allowed to receive natural precipitation throughout the experiment. To ensure that drought did not develop, neutron probe measurements were taken weekly, and control plots were irrigated whenever volumetric soil moisture content at the 25 cm depth was $<0.25\ m^3\ m^{-3}$ (soil water potential ≈ -0.1 MPa). Irrigation plus rainfall in the control plots totaled 100 mm in June 2003, 368 mm in August 2003, 209 mm in June 2004, and 149 mm in August 2004.

Rooting depth was evaluated by collecting root images at 1.2-cm intervals to a depth of 100 cm with a BTC 2 minirhizotron camera and BTC I-CAP image capture system (Bartz Technology Co., Santa Barbara, CA). Root images were collected at the beginning and end of each drought treatment, with the exception of late-summer 2003, when images were only captured at the end of the drought treatment. Each image was visually inspected, and data were recorded as the number of live roots visible in each frame.

Forage yield and soil water content data were analyzed as a randomized complete block split-plot design with four replications using the SAS Proc GLM procedure (SAS Institute, 2001). Whole plots consisted of irrigation treatments with grass species and mixture complexity as subplots. Years and harvest months were considered random effects for forage yield. Because of the repeated nature of the measurements, soil water content data were analyzed separately for each date. Mean separation was by LSD. There were two replications per rainout shelter and adjacent control area. Means and standard errors were calculated separately for each 30-min time step for the soil water potential data and for each 6.75-cm depth segment for the root counts.

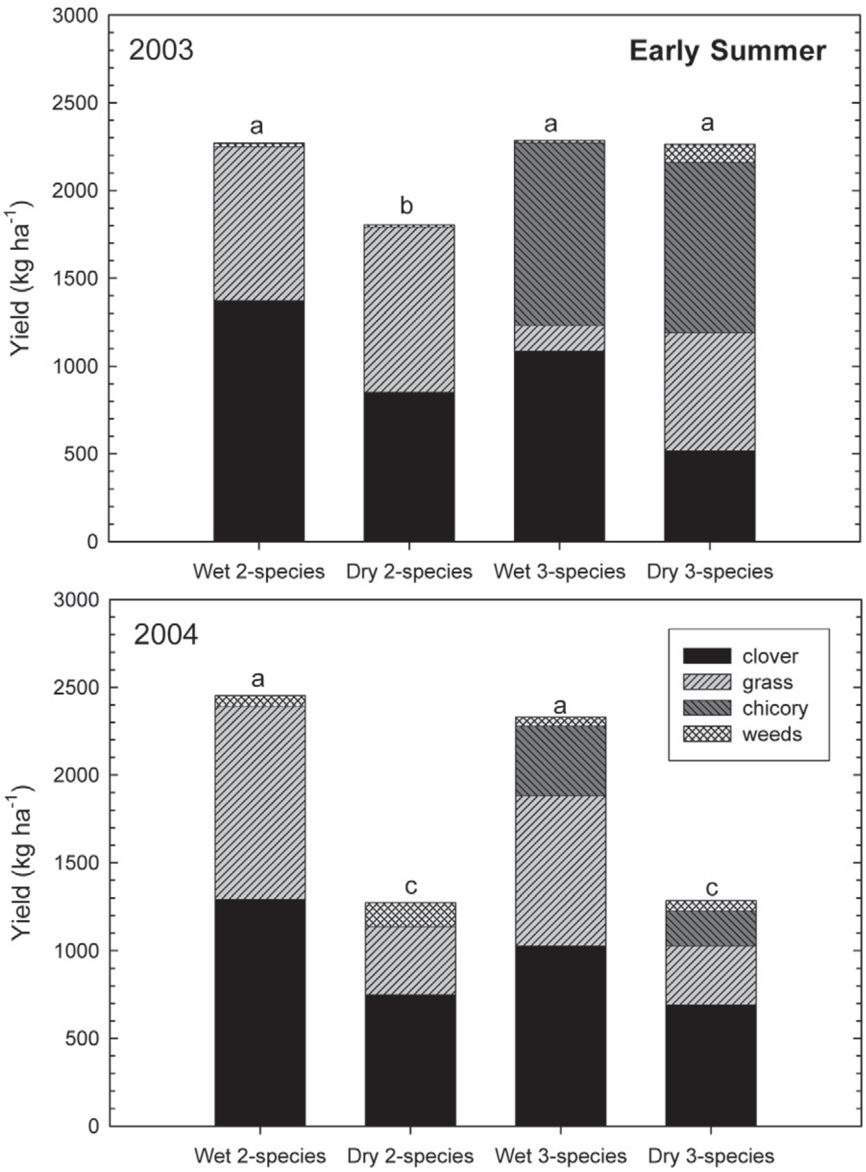

Figure 1. Early-summer yields for well-watered (wet) and drought-stressed (dry) two-species grass–legume and three-species grass–legume–chicory mixtures. Means with the same letter are not significantly different at $P = 0.05$.

RESULTS AND DISCUSSION

Forage Yield

A significant grass species × irrigation treatment interaction was found ($P = 0.03$). Plots containing orchardgrass exhibited 18% greater yield than plots containing perennial ryegrass under well-watered conditions, whereas grass species had no effect on yield under drought stress. However, no significant grass species × mixture complexity × irrigation interaction existed ($P = 0.37$), suggesting that the responses of both two- and three-species mixtures to water stress were similar regardless of the grass species present in the mixture. A significant year × irrigation × mixture complexity interaction was observed (P = 0.04). In early-summer (Fig. 1) and late-summer 2003 (Fig. 2), drought stress reduced yield relative to well-watered controls for the two-species but not the three-species mixtures. However, in 2004, yield in both mixtures was significantly reduced by the drought treatment in both early and late summer regardless of mixture complexity. Neither year nor mixture complexity affected yield of the well-watered plots when treatments were imposed in early-summer (Fig. 1). However, the longer duration of the growth period in late-summer 2003 resulted in greater yield for all treatments compared with the three other measurement periods. The well-watered and drought-stressed two-species mixtures each had 36% greater yield in late- compared with early-summer 2003, whereas late-summer yields for the three-species mixtures only increased by 10% in the well-watered and 6% in the drought-stressed treatments. Thus, the two-species mixtures had greater yield than the three-species mixtures under well-watered conditions in late-summer 2003. It is not clear why the two-species mixtures were more responsive than the three-species mixtures to the longer growth period. However, the results suggest that the interaction between harvest timing and species composition could have a significant impact on the relative yield of mixtures of differing complexity.

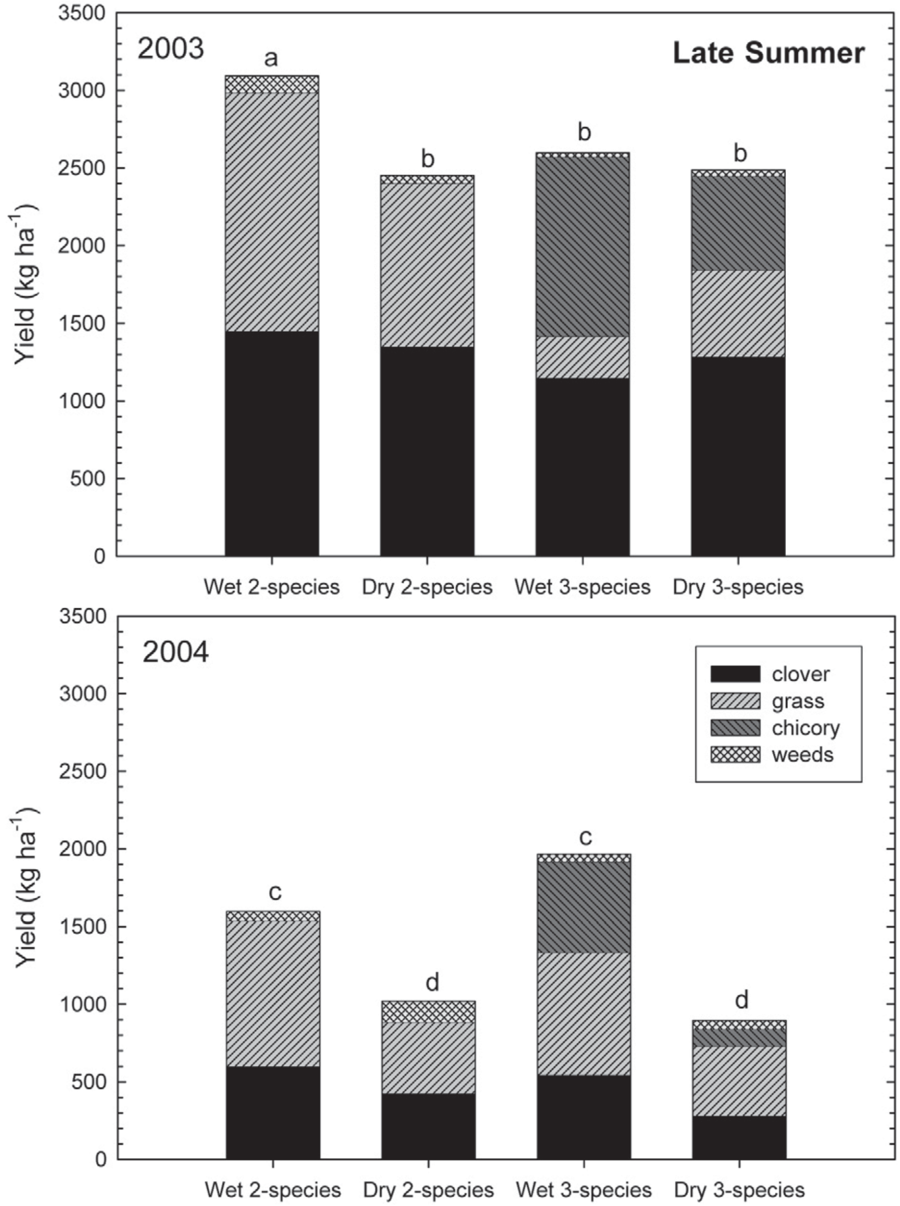

Figure 2. Late-summer yields for well-watered (wet) and drought-stressed (dry) two-species grass–legume and three-species grass–legume–chicory mixtures. Means with the same letter are not significantly different at P = 0.05.

Adding chicory to the grass–legume mixtures reduced the negative impact of drought on forage yield in 2003 but not in 2004. The 2003 results support the observation that a five-species mixture dominated by chicory had significantly greater yield than simple grass–legume mixtures under dry conditions (Skinner et al., 2004). Sanderson et al. (2005) also observed no difference in herbage yield among mixtures containing two, three, six, or nine species when moisture was plentiful, but during a dry year the two-species mixture produced less herbage than the other mixtures. They concluded that planting a mixture of grasses, legumes, and chicory would improve yield during dry years.

In the current study, the positive effect of chicory on yield under dry conditions was not sustained in 2004. To understand why, it was necessary to examine changes in species composition of the three–species mixture over time. The proportion of chicory in the three-species mixtures decreased throughout the experiment in the dry treatment, from 39% of harvested biomass in early-summer 2003 to 9% in late-summer 2004 (Table 1). The proportion of chicory in the well-watered treatment was similar to that in the dry treatment in early-summer of each year but was greater than in the dry treatment by late-summer. In general, the grass proportion of the three-species mixture tended to increase as the proportion of chicory decreased. White clover averaged about 40% of harvested biomass in the three-species mixtures, and while there was variation from harvest to harvest, no tendency for white clover to increase or decrease over time was detected.

Chicory tends to be a relatively short lived species in humid-temperate pastures and rarely persists beyond 3 to 4 yr (Li et al., 1997; Belesky et al., 1999; Sanderson et al.,

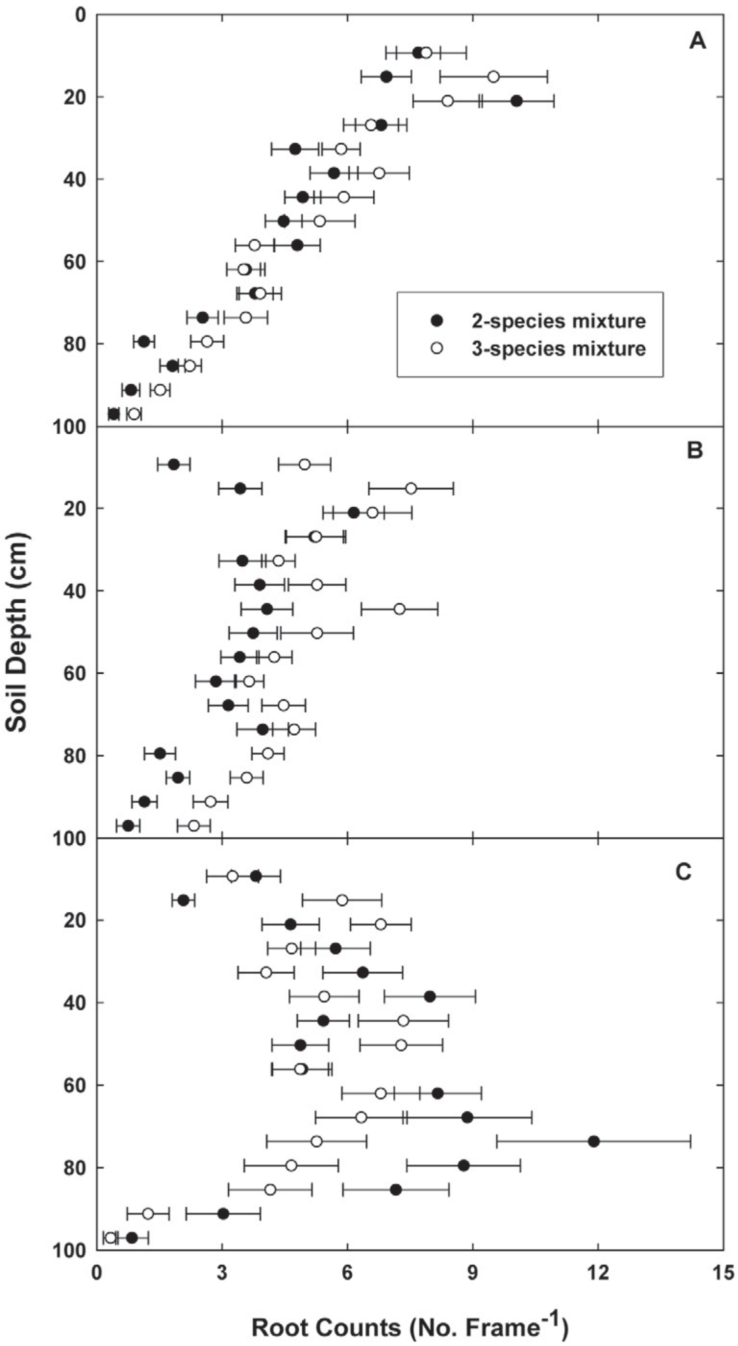

Figure 3. Root distribution with soil depth for two- and three-species mixtures. (A) Initial distribution at the beginning of first drought-stress treatment (6 June 2003). (B) Distribution beneath well-watered plots on 1 July 2003. (C) Distribution beneath drought-stressed plots on 1 July 2003. Each point represents the mean of four replications and five frames (6.75 cm depth). Error bars represent ± 1 SE.

2005; Skinner et al., 2006), although inclusion in mixtures with a combination of grasses and legumes (Kunelius and McRae, 1999) or with reduced nitrogen application (Belesky et al., 2000) has increased chicory persistence in some instances. In this study, a steady loss of chicory occurred throughout the experiment when plants were subjected to drought stress. However, in the well-watered treatment, chicory only declined between the late-summer 2003 and early-summer 2004 harvests (Table 1), suggesting that most mortality in the well-watered plots occurred during winter. Skinner and Gustine (2002) found that well-watered chicory was more susceptible to winter injury than was chicory that had been exposed to drought stress during the previous summer. The pattern of chicory loss in the current study is consistent with that observation. Increased loss of chicory during the summer due to drought stress appeared to negate any potential benefits that might have derived from reduced mortality during winter.

Because of the loss of chicory, especially in the dry treatment, the three-species mixtures differed little from the two-species mixtures in terms of species composition by the end of the experiment. It appeared that the small amount of chicory present in 2004 was not sufficient to confer the yield benefits under drought stress that chicory provided in 2003. To understand how the presence of chicory improved productivity under drought, the remainder of this article focuses on the differences that existed between drought-stressed two- and three-species mixtures in 2003.

Root Growth

At the beginning of the first drought treatment in early-summer 2003, the three-species mixtures had greater root counts than the two-species mixtures at the lowest soil depths, although differences between mixtures were small (Fig. 3A). The median rooting depth (50% of roots located both above and below that depth) for both mixtures was 33 cm. At the harvest 1 mo later, root counts near the soil surface had decreased for both mixtures in the well-watered treatment, with some increase occurring below a depth of about 40 cm (Fig. 3B). The median rooting depth had decreased to 44 cm for both mixtures. However, differences between the two- and three-species mixtures at the lowest soil depths had become slightly more pronounced in the well-watered plots. In the drought-stressed plots (Fig. 3C), both mixtures had decreased root counts in the upper 40 cm of the soil profile. However, a strong proliferation of roots had occurred at lower depths for both mixtures, but most especially beneath the two-species mixtures. Under drought stress, the two-species mixtures had more roots below a depth of about 70 cm than did the three-species mixtures. The median rooting depth had decreased to 62 cm for the two-species and 50 cm for the three-species mixture. Similar rooting patterns were observed at the end of the late-summer drought treatment (data not shown). Blum and Ritchie (1984) found that crown root numbers were reduced when the soil surface water content was low; they concluded that limiting crown root numbers caused compensatory growth of existing roots, which subsequently reached deeper soil layers. Skinner et al. (1998) also observed that root relative growth rates increased as soil depth increased, with deep roots in dry furrows growing faster than roots in wet furrows.

By 2004, little difference in root numbers existed between the drought-stressed two- and three-species mixtures at depths above 40 or below 60 cm (data not shown). However, the three-species mixture tended to have greater root numbers between about 40 and 60 cm. This difference was observed at the beginning of the drought treatment in early summer and persisted throughout the year. In general, root counts at all depths tended to be lower in 2004 than in 2003.

The original hypothesis was that the deep-rooted nature of chicory would improve access to moisture located deeper in the soil profile that would not normally be accessible to simple grass–legume mixtures. Indeed, Skinner et al. (2004) found that a five-species mixture containing chicory had a much greater proportion of its root biomass below a depth of 30 cm than did two simple grass–legume mixtures. They proposed that deeper rooting by chicory could have allowed it to extract the bulk of its water from deeper in the soil profile, leaving more water available near the surface for use by other species. Alternatively, they suggested that through the process of hydraulic lift (Richards and Caldwell, 1987; Caldwell et al., 1998), chicory may have redistributed water from moist soil layers at depth to more shallow layers, where it would then be available for uptake by shallow-rooted species. The root growth data in the current study failed to support the hypothesis that chicory improved access to moisture deep in the soil profile under drought stress. Although the three-species mixtures had an inherently deeper root distribution under well-watered conditions at the beginning of the experiment, the two-species mixtures had a more plastic response to drought, exhibiting a greater decrease in root counts in the upper soil along with a greater increase at lower depths. Thus, the improved performance under drought by the three-species mixtures in 2003 was not due to greater access to soil moisture through root proliferation. Other explanations must be found for the improved yield under drought for plots containing chicory.

Soil Water Relations

The effect of root distribution on soil moisture extraction from the drought-stressed plots in 2003 was considered next. There was no significant effect of mixture complexity on soil water content at any depth in 2003 (Fig. 4). The greatest change in soil water content during each drought period occurred within the top 25 cm, whereas very little change was observed at the 75-cm depth, which remained near field capacity throughout the drought treatment. Similar results were observed at the 50- and 75-cm depths in 2004 (Fig. 5). However, the 25-cm depth became significantly drier in 2004 compared with 2003, reaching soil water contents as low as 0.13 $m^3\ m^{-3}$ in 2004, whereas the lowest soil water content in 2003 was 0.16 $m^3\ m^{-3}$. Soil at the 25-cm depth under the three-species mixture also tended to become progressively drier than under the two-species mixture throughout the year, so that soil water content at 25 cm was significantly lower in the three-species mixture throughout the late-summer 2004 drought treatment. It is not clear why differences in soil

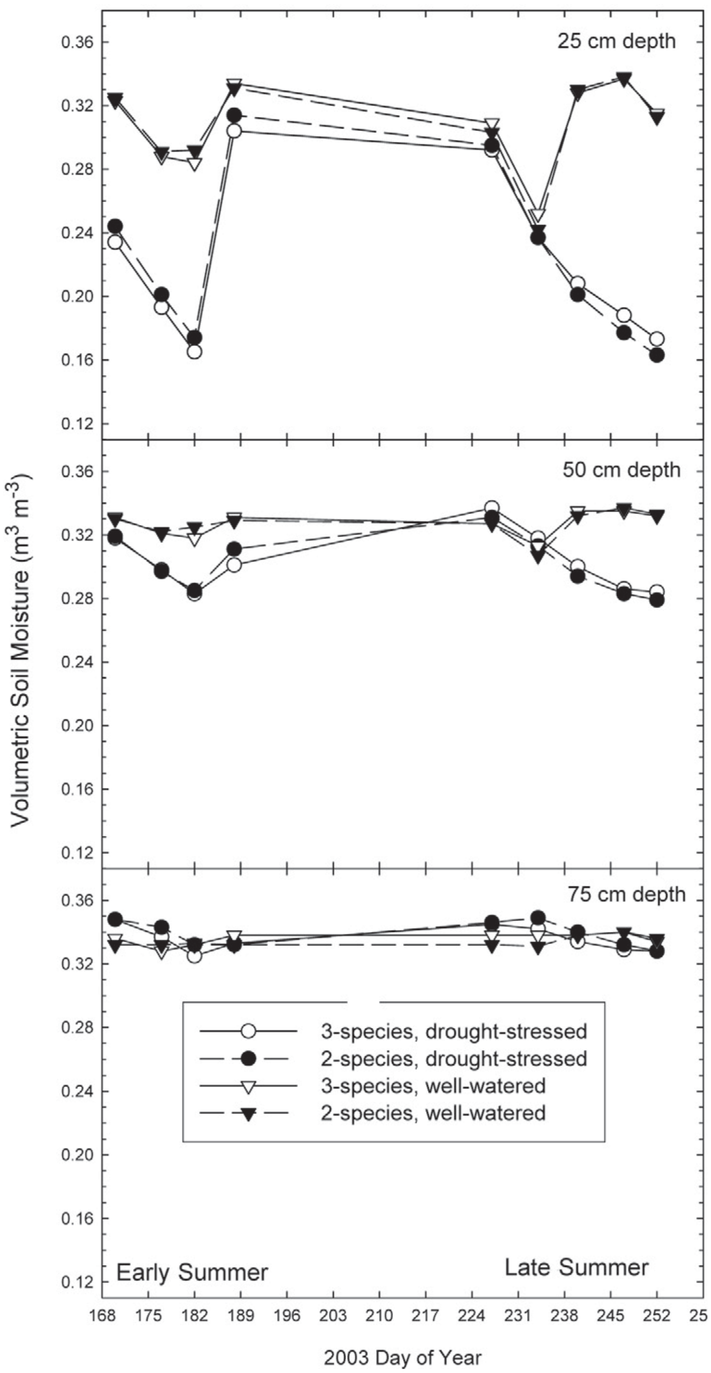

Figure 4. Effect of drought treatments on soil volumetric water content at 25-, 50-, and 75-cm depths in 2003. No significant differences existed between the two- and three-species mixtures in 2003 for either moisture treatment on any date.

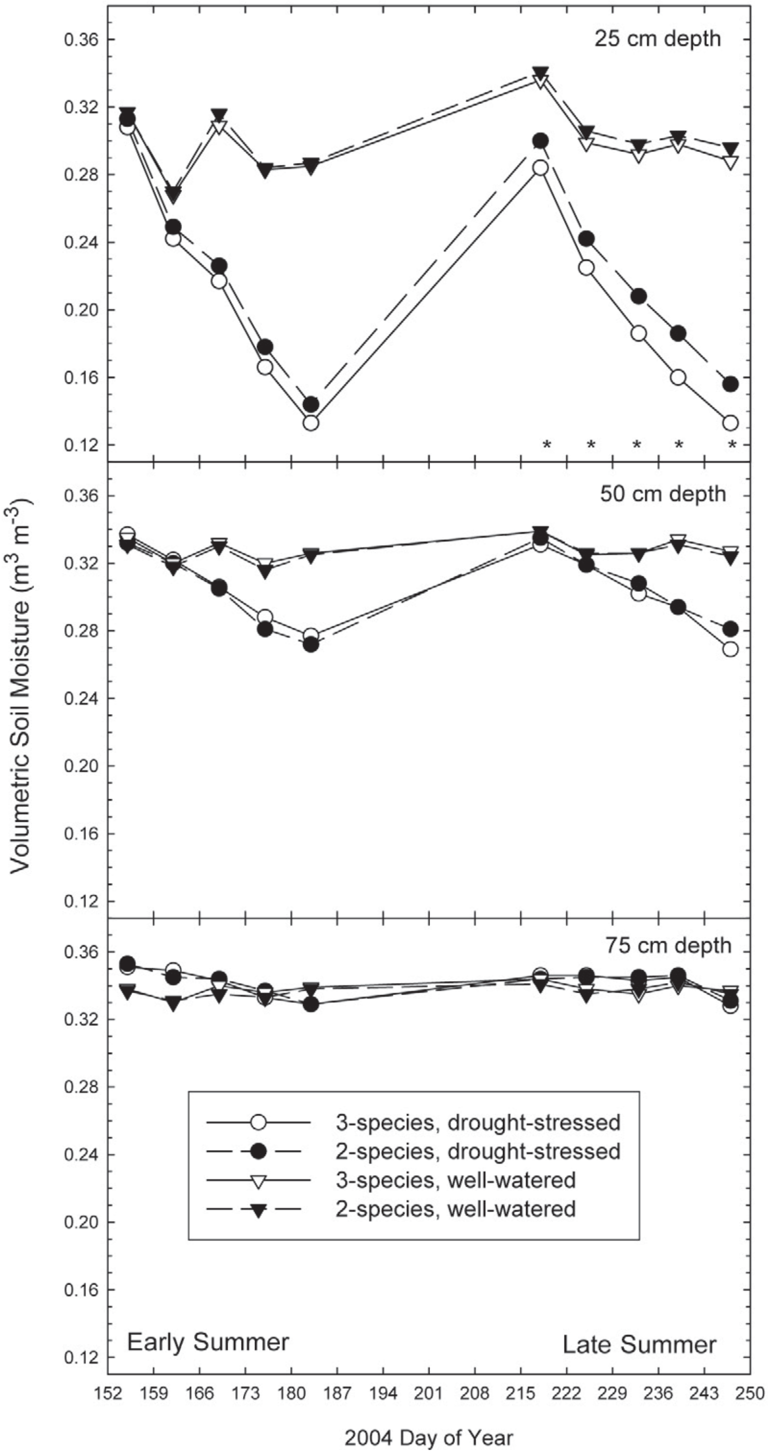

Figure 5. Effect of drought treatments on soil volumetric water content at 25-, 50-, and 75-cm depths in 2004. * indicates dates when significant differences occurred between the two-and three-species mixtures under drought stress.

moisture content developed in late-summer 2004 since that was the period when the two- and three-species mixtures were most alike, with chicory by that time comprising less than 10% of the three-species mixtures under drought (Table 1).

The limited change in soil moisture at 75 cm suggests that increased root counts at lower depths for the two-species mixtures in 2003 did not result in a greater proportion of their moisture uptake coming from deeper soil layers. Proffitt et al. (1985) found that deep-rooted plants were able to extract more water from greater depths and that the deeper roots became increasingly more efficient at extracting water as the soil dried. This was not the case in the current experiment. In this experiment, considerable moisture remained available throughout the rooting profile at the end of the drought treatments, reducing dependence on deep soil moisture. There was also no apparent relationship between the number of roots at depth and changes in soil water content. Perhaps the deeper soil moisture would have become more important if the drought treatment had continued long enough for the surface moisture to be more completely depleted.

When the surface is dry, plant root systems with access to deep soil moisture have the ability to transfer water from depth to the surface through the process of hydraulic lift (Richards and Caldwell, 1987; Caldwell et al., 1998). A defining characteristic of hydraulic lift is the diurnal fluctuation in soil water potential near the soil surface due to drying during the day followed by partial rewetting at night. In this experiment, both the two- and three-species mixtures exhibited the diurnal soil water potential fluctuations at a depth of 25 cm that are characteristic of hydraulic lift (Fig. 6). The diurnal fluctuations were observed at soil water potentials greater than −0.1 MPa, suggesting that nighttime water potential gradients from plants to the soil were established under relatively wet soil moisture conditions at this location. This was not surprising given the frequency that nighttime atmospheric water content becomes saturated in humid-temperate climates.

Soil water potential measurements are highly sensitive to changes in soil temperature (Wiebe and Brown, 1979). Even though measurements were corrected to a common temperature of 25°C, the possibility remained that the increased water potential observed at night could simply have been an artifact related to the concurrent soil cooling that also occurred at night. To test for that possibility, changes in soil temperature and water potential between consecutive 30-min measurements in early-summer 2003 were compared during periods of increasing nighttime soil water potential. Nighttime soil water potential generally increased by less than 0.01 MPa during any given 30-min period. At the same time, the change in soil temperature could be either positive or negative but was usually less than ± 0.1°C. There was no significant relationship between changes in soil water potential and changes in soil temperature ($r = -0.03$). During any given night, soil temperature tended to initially increase for 1 to 2 h, followed by another 1 to 2 h of little or no change before temperature decreased for the rest of the night (data not shown). However, soil water potential increased throughout the nighttime period. This suggests that the increased water potential observed during the night resulted from the transfer of water from deeper soil layers and was not an artifact of decreasing soil temperature.

Because significant soil moisture depletion only occurred from the upper 50 cm, moisture from deep in the soil profile remained accessible to all species, making nighttime water transfer from deep to shallow soils possible for both mixtures. The relatively limited depletion of soil moisture from depths below 25 cm suggests that transfer from deeper layers played only a limited role in meeting the water requirements of both mixtures. Brown et al. (2005) found that in deeper soils, chicory was capable of extracting water to a depth of 1.9 m. The deeper tap-root system of chicory could lead to increased water uptake under prolonged exposure to drought, where soil moisture would be depleted to a greater depth.

As was observed for soil water content at 25 cm (Fig. 4), there was no significant difference between mixtures for soil water potential in early-summer 2003 (Fig. 6). However, the three-species mixtures maintained higher soil water potentials in late-summer 2003. Thus, the three-species mixtures had increased yield under drought in early-summer 2003 while using a similar amount of water compared with the two-species mixtures. This suggests that the three-species mixtures exhibited greater water use efficiency than the two-species mixtures in early-summer 2003. The higher soil water potential in the three-species mixtures in late-summer 2003 combined with similar yields between mixtures suggests that water use efficiency may also have been higher in the three-species mixtures during late summer as well, although the evidence is less conclusive than for the early-summer period. No published studies are available that directly compare the water use efficiency of all the species included in this study. In particular, little information on the water use efficiency of chicory exists, although Brown et al. (2005) suggested that its water use efficiency was similar to that of alfalfa (*Medicago sativa* L.). Without direct comparisons among the individual species, it is impossible to determine if the apparent enhanced water use efficiency of the three-species mixtures was due to the greater efficiency of chicory or if interactions among species resulted in greater water use efficiency for the mixture as a whole.

CONCLUSIONS

Adding chicory to grass–legume mixtures reduced the susceptibility of the resulting three-species mixtures to drought stress during the year after planting. However, the

Table 1. Chicory persistence in well-watered (wet) and drought-stressed (dry) grass–legume–chicory mixtures. Mean separation was by LSD.

Treatment date	Wet	Dry
	% Chicory	
Early-summer 2003	45 a†	39 ab
Late-summer 2003	44 a	24 bcd
Early-summer 2004	17 cd	16 cd
Late-summer 2004	27 bc	9 d

†LSD = 17%; means followed by the same letter are not significantly different at $P = 0.05$.

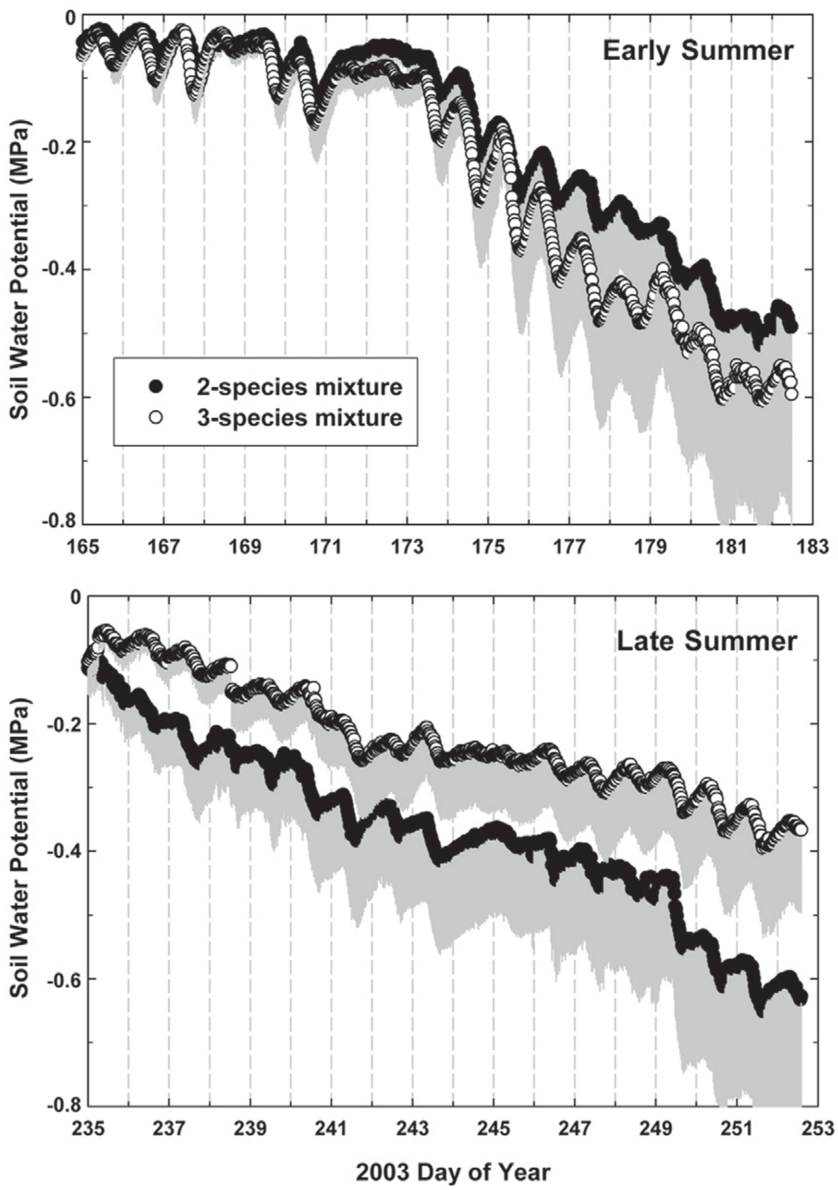

Figure 6. Soil water potential at 25-cm depth during the final 18 d of drought stress in 2003 for two-species (grass–legume) and three-species (grass–legume–chicory) mixtures. Standard errors are indicated by gray shaded area. Only negative standard error values are shown to improve clarity.

increase in drought tolerance was only realized as long as chicory was a significant proportion of the mixture. The amount of chicory needed to confer improved drought tolerance was not precisely determined but appeared to be somewhat greater than 20% by weight of the total forage biomass. Improved drought tolerance of the three-species mixture was probably related to greater water use efficiency rather than to greater access to and extraction of available soil moisture. All mixtures had roots that extended to 1-m depth and appeared capable of nighttime transfer of soil moisture from deep to shallow soil layers. However, because very little soil moisture was removed from the 75-cm depth, this transfer did not appear to affect the relative drought tolerance of the two- and three-species mixtures, primarily because both mixtures had access to water from the same portion of the soil profile.

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